

# Elastic/Inelastic Measurement Project

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## Fuel Cycle

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**NEUP Final Report  
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**Performance Period: ~Jan 2013 – 31 Dec 2015+**

Abstract/Work Scope Overview & Summary:

The work scope involves the measurement of neutron scattering from natural sodium ( $^{23}\text{Na}$ ) and two isotopes of iron,  $^{56}\text{Fe}$  and  $^{54}\text{Fe}$ . Angular distributions, *i.e.*, differential cross sections, of the scattered neutrons will be measured for 5 to 10 incident neutron energies per year. The work of the first year concentrates on  $^{23}\text{Na}$ , while the enriched iron samples are procured.

Differential neutron scattering cross sections provide information to guide nuclear reaction model calculations in the low-energy (few MeV) fast-neutron region. This region lies just above the isolated resonance region, which in general is well studied; however, model calculations are difficult in this region because overlapping resonance structure is evident and direct nuclear reactions are becoming important. The standard optical model treatment exhibits good predictive ability for the wide-region average cross sections but cannot treat the overlapping resonance features. In addition, models that do predict the direct reaction component must be guided by measurements to describe correctly the strength of the direct component, *e.g.*,  $\beta_2$  must be known to describe the direct component of the scattering to the first excited state. Measurements of the elastic scattering differential cross sections guide the optical model calculations, while inelastic differential cross sections provide the crucial information for correctly describing the direct component.

A summary of activities occurring during the performance period are described in this report.

## Overview of Laboratory

The accelerator at the University of Kentucky, a 7-MV single-ended Model CN Van de Graaff, is used primarily as a factory for monoenergetic neutrons. The pulsing/bunching system is located inside the high-voltage terminal. Proton, deuteron,  $^3\text{He}$ , or  $^4\text{He}$  ions are generated in an rf bottle. Ions are pulsed by sweeping them through an elliptical path across an aperture. The beam then passes through a double-gap buncher capable of achieving  $\sim 1$  ns pulse widths on target.



Fig 1. View of the neutron time-of-flight facility. The accelerated beam enters from the right and produces neutrons in the gas cell at the end of the beam line. The scattering sample is hung in the emerging fluence of neutrons, typically 5.5 cm from the end of the gas cell. The detector shielding appropriate for 4-meter neutron detection measurements is shown on the carriage.

The accelerator delivers the beam to one of seven beam lines in two experimental halls. One experimental hall and a beam line were specially constructed with a 4-meter flight path for neutron time-of-flight (TOF) measurements. This room has a high ceiling and a false floor, which covers a 2.8-m deep pit. Neutrons are produced with the reactions  $^3\text{H}(p,n)$ ,  $^2\text{H}(d,n)$ ,  $^3\text{H}(d,n)$ , and  $^7\text{Li}(p,n)$ . Tritium and deuterium gases are contained in cells constructed of stainless steel and lined with a tantalum foil and beam stopper. Detectors are mounted on a carriage which can be rotated to cover scattering angles up to  $155^\circ$ . The carriage supports a full-length collimation system.

Neutron production rates are recorded with a long counter and a forward monitor (FM) liquid scintillator. The long counter records the time-integrated fast neutron production during a data run. The FM is placed at  $45^\circ$  and high on the wall to provide a direct, collimated view of the gas cell. On-pulse source neutrons are identified in the FM by TOF and pulse shape discrimination (PSD).

Neutrons scattered from the sample of interest are detected and analyzed using TOF techniques. A  $\text{C}_6\text{D}_6$  liquid scintillator is employed for the 'MAIN' neutron detector. Pulse-shape discrimination (PSD) is used to separate neutron and  $\gamma$ -ray events in the detector and remove unwanted  $\gamma$ -ray background. An example of a TOF spectrum from recent scattering measurements on  $^{54}\text{Fe}$  is shown in Fig 2.

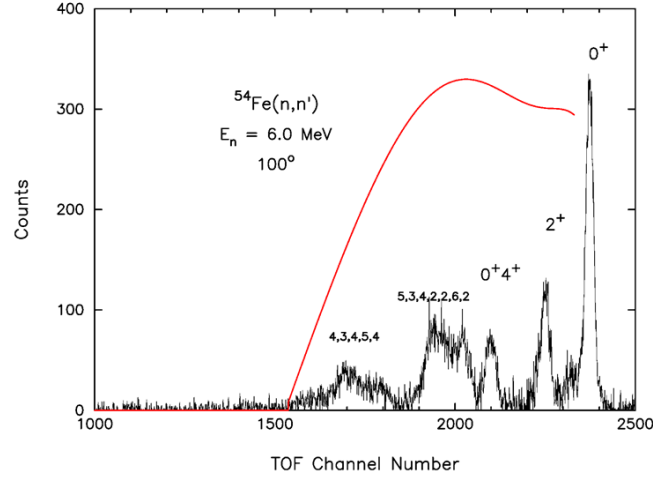


Figure 2. TOF spectrum of 6.0-MeV neutrons scattered at  $100^\circ$  from  $^{54}\text{Fe}$ . Flight time increases to the left. Peaks corresponding to scattering to the various final states in  $^{54}\text{Fe}$  are labeled. The red curve is representative of the MAIN detector efficiency.

For the MAIN neutron detector efficiency measurement, the detector carriage is repositioned to view the gas cell directly. The  $T(p,n)$  angular distribution specifies how many neutrons are emitted toward the MAIN detector at angle  $\theta_{lab}$ , and the  $T(p,n)$  kinematic angular variation specifies the energy of these neutrons.

Normalization of  $(n,n_k)$  angular distributions to absolute  $(n,n_k)$  cross sections is performed by comparison to the angular distributions of  $^1\text{H}(n,n)$ , which is generally known to 0.50% in the fast region.

All measurements are corrected for neutron attenuation and multiple scattering in the samples using the code MULCAT, developed at the University of Kentucky. The code performs iterative Monte Carlo calculations, taking as input the normalized experimental angular distribution as determined from the data analysis. The Kentucky group has years of experience with MULCAT on medium-mass single-element samples.



Fig. 3. Singles  $\gamma$ -ray measurement configuration. Much of the TOF collimation is removed and the detector placed  $\sim 1.2$  meters from the sample. The carriage is shown at  $90^\circ$  to the beam direction.

For singles  $\gamma$ -ray detector measurements, the carriage in the neutron hall is configured as shown in Fig. 3. The HPGe detector has a simple cylindrical geometry BGO Compton shield to improve the signal-to-

background ratio. Both neutrons and  $\gamma$  rays will create events in the detector, so neutron TOF techniques are used to diminish neutron-induced background in the  $\gamma$ -ray spectrum.

Both  $\gamma$ -ray angular distributions and  $\gamma$ -ray neutron-energy-dependent excitation functions are measured with this carriage configuration. The  $\gamma$ -ray yields must be corrected for HPGe detector efficiency and incident neutron and outgoing  $\gamma$ -ray attenuation and multiple scattering in the sample. Sample-related corrections are performed with an in-house code GAMBIT which is based upon the Engelbrecht treatment for the  $(n,n'\gamma)$  reaction on cylindrical samples.

For angular distribution measurements, the incident neutron energy is chosen and spectra are typically taken for detector angles of  $40^\circ$ – $150^\circ$ . For  $\gamma$ -ray excitation functions, the detector carriage is positioned at  $\theta_\gamma = 90^\circ$  or  $125^\circ$  and spectra are taken as the incident neutron energy is raised. At  $125^\circ$  the  $a_2P_2$  term in the angular distribution is identically zero and the  $a_4P_4$  term is typically small,  $\ll 7\%$ . An excitation function measurement therefore returns  $A_0$  coefficients as a function of bombarding energy. The  $A_0$  coefficient is proportional to the production cross section for individual  $\gamma$  rays. The shape of the excitation function is also sensitive to the spin of the parent excited levels. If fidelity in  $\gamma$ -ray energy is a concern, measurements can be performed at  $90^\circ$  where no Doppler shifts are observed.

To convert  $A_0$  coefficients to  $\gamma$ -ray production cross sections, we compare properly corrected yields to a  $\gamma$ -ray cross section standard. Unfortunately high-quality  $\gamma$ -ray standards do not exist for few-MeV  $(n,n'\gamma)$  scattering, although several are under development. We frequently choose to make a comparison to the  $^{56}\text{Fe}$ ,  $^{48}\text{Ti}$ ,  $^{51}\text{V}$ , and  $^{27}\text{Al}$  inelastic cross sections from the ENDF evaluation. These reference cross sections must be averaged over the incident neutron energy spread. Our uncertainty in determining the conversion is  $\sim 6\%$ . Although not considered an absolute measurement, the cross section values obtained have been amazingly consistent with results obtained at GELINA and nELBE.

## Task/Objective/Deliverable/Milestone 1

Title: Measurements of Elastic and Inelastic Differential Cross Sections

### Description

At the University of Kentucky Accelerator Laboratory (UKAL), neutron elastic and inelastic scattering differential cross sections and/or  $\gamma$ -ray production cross sections at 5 to 10 incident neutron energies ( $E_n$ ) will be measured each year. Measurements are made on samples of  $^{23}\text{Na}$ ,  $^{54}\text{Fe}$ , and  $^{56}\text{Fe}$ .

### Accomplishments

Table 1. Summary of Experimental Measurements.

#	Run	Target	Incident Neutron Energies (MeV)
1	Jan2013	23, C	2.44, 3.80
2	Feb2013	23, C	4.45, 6.37
3	Jun2013	54, natFe, C	3.0, 4.0
4	Sep2013	54, natFe, C	2.25, 2.50, 2.75
5	Jan2014	54(n,n' $\gamma$ )	ExcFn 1.5 to 4.7
6	Jan2014	54, C	4.5
7	Mar2014	54, natFe, C	2.0, 3.5
8	Jun2014	54	5.0, 6.0
9	Jul2014	54, C	5.0, 6.0
10	Nov2014	56, C	2.0, 2.5, 3.0
11	Jan2015	56, C	7.0, 8.0
12	May2015	56, C	3.5, 4.0, 4.5
13	Jun2015	56(n,n' $\gamma$ )	ExcFn 1.0 to 4.7 $\gamma$ -ray Ang Dist 4.6
14	Oct2015	56, C	2.25, 2.75
15	Jan2016	56, C	1.3, 1.5, 1.8

Notation: All measurements are (n,n') unless otherwise noted. Targets are specified as: 23= $^{23}\text{Na}$ , natFe= $^{nat}\text{Fe}$ , 54= $^{54}\text{Fe}$ , 56= $^{56}\text{Fe}$ , C= $^{nat}\text{C}$ . During excitation function runs, the targets  $^{nat}\text{Al}$ ,  $^{51}\text{V}$ , and  $^{nat}\text{Ti}$  were also measured. ExcFn indicates the  $\gamma$ -ray production cross sections were measured.

Each angular distribution or excitation function typically takes ~4 days. Thus ~128 days, ~3072 hours, or ~43 days/year were invested during the performance period with beam-on-target.

## **Task/Objective/Deliverable/Milestone 2**

Title: Analyze Data, Deliver Results to Data Evaluators, Report Results at Conferences

### Description

Neutron scattering data require lengthy analysis which must be carefully performed and checked. Periodic updates are sent to data evaluators and information is exchanged with other groups who have complementary information in order to assure the highest quality results in the databases. Information exchange also includes maintaining collaborative efforts with knowledgeable colleagues outside the project in order to obtain helpful suggestions on experimental techniques. Attendance at meetings is required where analysis issues and reaction model interpretations are discussed and to develop a better understanding of end-user applications and concerns.

### Accomplishments

#### $^{23}\text{Na}$

Neutron scattering measurements on  $^{23}\text{Na}$  at thirteen energies in the  $E_n = 1.5\text{-}4.0$  MeV region were completed. Overall uncertainty was estimated at 3% from data reduction issues, plus 6% from T(p,n) cross section uncertainties, plus a likely ~4% from attenuation and multiple scattering corrections, amounting to an overall 8% uncertainty in the elastics. The experimental angle-integrated elastic cross sections track the ENDF evaluation values extremely well with a few exceptions.

Sodium-23  $\gamma$ -ray production cross sections were given to the GELINA group (Arjan Plompen) at the Institute for Reference Materials and Measurements. In return, the group supplied recent measurements of  $\gamma$ -ray production from the IRMM lab. Our results appear entirely consistent with the IRMM results. The agreement implies that our actual neutron energy spread is significantly less than we have usually quoted over the last quarter of a century. This is especially apparent in the  $\gamma$ -ray production cross sections for the 2639-keV transition, where the data points track the sharp resonances exactly. We had hints of this earlier in our comparison to the CSISRS data of Perey-1977 and Kopecky-1997.

Sodium-23 results were sent to data evaluator Toshihiko Kawano (LANL) in March 2013.

The complete results for  $^{23}\text{Na}$  cross sections were sent to Giles Noguere of the CEA for use in updating the JEFF-3.1.2 data library. Predictions for integral experiments using that evaluation are deficient compared to the current ENDF/B-VII.1 and JENDL-4.0 data libraries.

Sodium-23 neutron and  $\gamma$ -ray results were sent to EXFOR and were assigned CSISRS/EXFOR reference number 14403 by ENDF evaluator Stanislav Hlavac of the Slovak Academy of Sciences.

Partial Sodium-23 results were published by former postdoc Ajay Kumar in the Journal of Radioanalytical and Nuclear Chemistry. Measurements were compared with the predictions of the light particle-induced reaction code TALYS. The TALYS calculations reproduce forward angle scattering but have difficulty with relative minima in the elastic differential cross section and large angle scattering.

Sodium-23 neutron and  $\gamma$ -ray results are published in Nuclear Physics A (April 2015).

A reaction mechanism interpretation of the  $^{23}\text{Na}$  cross section in the 1 to 4 MeV range is rather difficult. This range is above the isolated resonance region but not yet smoothly varying. The differential cross sections are indicative of compound nucleus and direct reaction mechanisms; however, the compound nuclear portion may be influenced by isolated resonance effects not addressable within the optical model treatment. This is certainly the case for inelastic scattering to the second and higher inelastic levels, where the resonances are clearly resolved.

Initial optical model parameters are available from Strohmaier [Ann. Nucl. Energy **20**, 533, 1993] who examined  $E_n > 5$  MeV (n,x) data for the purposes of applying the results to radiation dosimetry. Our analysis provides information on the deviations that can be anticipated from the implementable reaction models in the  $E_n = 2$  to 5 MeV region.

In general, we find that the Strohmaier parameters provide an adequate description of the forward-angle elastic differential cross sections. The compound elastic process, apparent at angles  $> 90^\circ$ , is too large in the default calculation, indicating the imaginary potential,  $W_D$ , should be substantially reduced. Dispersive optical model calculations in this mass region also point to smaller absorption at lower energies [Nagadi, Phys. Rev. C **68**, 044610, 2003].

On the other hand, the shapes of the (n,n<sub>1</sub>) and (n,n<sub>2</sub>) differential cross sections, particularly the suppression or enhancement at forward versus backward angles, indicate the presence of direct coupling. This is a result of the strong deformations known in the neighbouring nuclei in this mass region which force inclusion of direct processes into descriptions of the scattering from inelastic channels at lower energies than is typical with coupled-channel treatments.

We completed coupled-channels (CC) reaction model calculations to interpret the  $^{23}\text{Na}$  results. Although optical model-based cross section calculations *will* be used for engineering applications in region below 5 MeV, no careful examination of the reaction mechanism has been performed anywhere in this mass region. (Most nuclei with  $Z < 20$  utilize only global parameters in the RIPL-3 database and EMPIRE code suite.) Nuclear structure interpretations of  $^{23}\text{Na}$  are rather limited. The most recent discussion is that of Durell [J. Phys A **5**, 302, 1972] which indicates that significant deformation is present in this mass region. The  $^{23}\text{Na}$  level scheme is generally discussed as rotational with strong core-excitation components. The large  $^{23}\text{Na}$  deformation impacts the differential cross sections.



Wick's Limit is often used to check the self-consistency of scattering cross sections. Its roots are in light optics, where the total absorption cross section for light can be related to the imaginary part of the forward-scattering amplitude. As such, Wick's Limit is expected to hold where the nuclear Optical Model provides a good description of the average cross sections. Wick's Limit should under-predict the  $0^\circ$  cross section at higher energies when additional reaction mechanisms are active. Wick's Limit is not an applicable concept in the isolated resonance region. We observe Wicks Limit only has limited validity in our  $^{23}\text{Na}$  data, which implies the elastic angular distributions predicted by the optical model treatments are suspect.

### $^{nat}\text{Fe}$

Elastic and inelastic neutron scattering angular distributions were measured at 6-8 incident neutron energies on  $^{nat}\text{Fe}$ . Statistical uncertainties on the neutron cross sections are well under the 7% desired for the elastic scattering angular distributions. Systematic uncertainties are still under study. Comparisons to ENDF evaluated data files show reasonably good agreement between measured and model cross sections for neutron elastic scattering cross sections. The agreement is mixed for neutron inelastic scattering cross sections.

Marcus McEllistrem examined our  $^{nat}\text{Fe}(n,n')$  differential cross sections with the coupled-channels code ECIS06. In contrast to our earlier  $^{23}\text{Na}$  work, the  $^{56}\text{Fe}$  cross section does not exhibit large resonance structure in the cross sections above  $E_n=2.7$  MeV. The cross sections fluctuate rapidly, but the average behavior should be treatable with an optical-model-like description.

### $^{54}\text{Fe}$

Iron-54 (n,n) angular distribution data were taken at 9 incident neutron energies during Year-2 and analyzed by postdoc Shaohua Liu. Statistical uncertainties on the neutron cross sections are well under the 7% desired for the elastic scattering angular distributions. Total uncertainties are near 9%. Comparisons to ENDF evaluated data files show very good agreement between measured and model cross sections for neutron elastic scattering. However our elastic scattering differential cross section results at  $E_n=3.0$  MeV and  $E_n = 4.0$  MeV indicate a slightly deeper diffraction minimum and less contribution from compound reaction strength at the larger angles than predicted in the 3.0 MeV ENDF database; our elastic data agree well with CSISRS data at the same incident neutron energy measured previously by Guenther et al. [Ann. of Nuc. Energy **13**, 601 (1986)].

A spherical optical model description is expected to be appropriate for  $^{54}\text{Fe}$ . Still, in the 1-5 MeV range the compound absorption component of the cross section is impacted by the nuclear structure. The behavior of inelastic cross sections is quite spectacular. While the  $E_n < 4$  MeV inelastic cross sections are well explained by the standard optical model, there is a sudden turn-on of some direct coupling mechanism between 4 and 5 MeV, which makes the first-inelastic forward peaked. This is present in both the 5 and 6 MeV data. We do not have a physical explanation for this sudden behavior.

The first inelastic channel,  $(n,n_1)$ , shows a significant direct reaction component at forward angles. The  $(n,n_1)$  channel reaction strength is stronger than predicted in the ENDF and JENDL databases principally due to the presence of the direct component.

The measured scattering strength to the combined  $(n,n_2) + (n,n_3)$  channels is only slightly larger,  $<10\%$ , than the JENDL database values; however the measured cross sections to the higher lying states,  $(n,n_{4-10})$ , are about 50% larger than the JENDL values.

Iron-54 is not expected to have low-lying rotational or vibrational character; however, pion scattering to the 2.538 MeV  $4^+$  state possesses an extremely strong hexadecapole character [Sheline et al., Czech. J. Physics 49, 1047 (1999)]. Note that this is not an electromagnetic hexadecapole (which would not be believable), possibly could appear as a strong  $\beta_4$  term in the coupled channels expansion treatment of the nuclear potential. We had hoped to observe this effect in the differential cross section of the  $4^+$  state.

Analysis of the  $^{54}\text{Fe}(n,n'\gamma)$   $\gamma$ -ray production cross sections,  $E_n = 1.5$  to 4.7 MeV, by undergraduate Aaron French are complete. Cross section normalizations with respect to  $\gamma$ -ray production on  $^{27}\text{Al}$ ,  $^{48}\text{Ti}$ , or  $^{51}\text{V}$  samples are amazingly consistent – the three conversion factors agree within  $<6\%$ . We observe that the  $(n,n_1)$  cross section follows the ENDF database extremely well at  $E_n < 2.2$  MeV and  $> 3.2$  MeV. The measured  $(n,n_1)$  cross section in the intermediate region is slightly higher. The summed total inelastic cross section is higher than the ENDF database in the  $E_n = 2.2 - 3.0$  MeV region by 20%. Above  $E_n = 4.0$  MeV the  $(n,\text{inel})$  cross section is lower than the ENDF database presumably because of unidentified weak  $\gamma$ -rays.

The manuscript for  $^{54}\text{Fe}$  is started and the TALYS and ECIS calculations have also been completed. We are performing final checks on the  $^{54}\text{Fe}(n,n_1)$  forward angle cross sections to confirm that the strength of the direct component is correct.

## $^{56}\text{Fe}$

Postdoc Anthony Ramirez has completed the analysis of all twelve  $^{56}\text{Fe}(n,n')$  angular distributions and the three  $^{56}\text{Fe}(n,n'\gamma)$  angular distributions measured with the exception of the January 2016 dataset. Elastic cross sections are consistent with the ENDF, JEFF, and JENDL databases. Analysis at angles less than  $50^\circ$  are challenging for the  $(n,n_1)$  channel because the elastic and inelastic peaks overlap significantly and this can lead to excessive scatter in the differential cross section values at those angles. This issue impacts the value for the angle-integrated  $(n,n_1)$  cross section, but we are beginning to believe it does not impact conclusions about the reaction model or strength of the coupled channels strength, which appear to be well constrained by the  $(n,\text{elas})$  and  $50\text{-}150^\circ$   $(n,n_1)$  differential cross sections.

Gamma-ray excitation functions,  $^{56}\text{Fe}(n,n'\gamma)$ , were measured between  $E_n = 1.0$  and 4.7 keV. Analysis is being performed by University of Dallas students.

Direct coupling is required to explain the elastic and 1<sup>st</sup> inelastic cross sections, but scattering to the higher lying states is compound-only. Our measured angle-integrated inelastic cross section to the first 2<sup>+</sup> state conforms to the shape expected from a optical model cross section. This confirms that measurements of the 2<sup>+</sup> cross section via (n,n' $\gamma$ ) at the spallation laboratories suffer from reverse-energy effects such as  $\gamma$ -ray feeding. While the  $\gamma$ -ray production cross sections at the spallation labs are correct, they do not provide un-ambiguous information for nuclear data reaction model refinement.

A vibrational treatment was adopted for the ground, 2<sup>+</sup>, and 4<sup>+</sup> states of the <sup>56</sup>Fe nucleus. At  $E_n=3.40$  MeV, the differential cross sections for scattering to the ground and 1<sup>st</sup> excited state of <sup>56</sup>Fe require direct coupling, but the 4<sup>+</sup> state can be explained simply by the compound process. At a slightly higher energy,  $E_n=3.50$  MeV, direct coupling to the 4<sup>+</sup> level suddenly is observed. Where does this direct component come from? Exciting the 4<sup>+</sup> state would have to occur via a double-quadrupole excitation or a single hexadecapole excitation. The former is unable to reproduce the 4<sup>+</sup> angular distribution and the latter is thought to be unlikely. Literature electromagnetic E2 transition rates (ENSDF) do not favor a 2-phonon description of the 4<sup>+</sup> state.

The lowest 3<sup>-</sup> level at  $E_x = 3.076$  MeV excitation in <sup>56</sup>Fe has caused a stir in recent years; see [D.Brown, presentation at USNDP-CSEWG Meeting, <sup>56</sup>Fe session, BNL, Oct 2014] and [N.Fotiades, et al., Phys. Rev. C, 81, 037304, (2010)]. Although present in the current ENSDF evaluation and the RIPL-3 level scheme file, measurements at spallation sources question its existence. Spallation neutron flux fluoresces the nucleus, and placements of  $\gamma$ -rays into a level scheme is ambiguous because  $\gamma$ -rays emitted following excitation can get 'hung-up' in long-lived states and isomers. Measurements at the University of Kentucky Accelerator Lab are free from this complication. We see the two requisite transitions, although they are very weak. Gamma-gamma coincidence data from Ron Nelson at LANSCE indicates the two transitions do not belong to the same level. It is not clear how to place these transitions into a level scheme at the present time.

### (n,n' $\gamma$ )

Inelastic neutron scattering measurements most reliably determine the cross section for the lowest few levels in a nucleus because they are well separated in excitation energy. Higher-lying states are not resolved in (n,n') TOF measurements, so the individual scattering cross sections cannot be measured directly. These cross sections can be extracted from  $\gamma$ -ray measurements. Unfortunately there are no high-quality  $\gamma$ -ray production standards in the  $E_n > 2$  MeV range. The best choices are (n,n' $\gamma$ ) on <sup>27</sup>Al, <sup>48</sup>Ti, and <sup>51</sup>V. We have analyzed our preliminary  $\gamma$ -ray excitation function data using these as reference standards. We find excellent agreement with the recently measured <sup>56</sup>Fe  $\gamma$ -ray production cross sections of Beyer [R. Beyer, et al., Nucl. Phys. A 927, 41 (2014)] and our own (n,n') cross sections. Also comforting is that the normalization factors with respect to <sup>48</sup>Ti and <sup>27</sup>Al are amazingly consistent.

## $^{12}\text{C}$

Peak fitting codes tend to model time-of-flight (TOF) peak shapes with one or two Gaussians plus one or two attached exponential or linear tails. We began a study of peak shape tailing in an effort to develop better methods for extracting the peak yields in a spectrum. We have discovered much of the low-side tailing in a TOF spectrum is due to multiple scattering. For medium-mass elements such as Fe, the effect introduces a slight tail to the otherwise Gaussian peak. For masses near  $A=23$ , the multiple scattering generates a prominent low-energy tail, which makes extracting peak yields problematic, as was the case with the  $^{23}\text{Na}$  data. For lighter nuclei, such as  $^{12}\text{C}$ , multiple scattering generates an extended shelf below the peak with a characteristic shape. It is important that the peak area and multiple scattering corrections be applied consistently in order to produce the true cross sections.

We have generated much  $^{12}\text{C}$  data over the last few years. Carbon samples were run during the  $^{23}\text{Na}$ ,  $^{\text{nat}}\text{Fe}$ ,  $^{54}\text{Fe}$ , and  $^{54}\text{Fe}$  measurements as cross-checks on our analysis procedures. We re-examined the published  $^{12}\text{C}$  cross sections in view of the peak shape revelations discussed in the previous paragraph. Generally, we observe slight enhancements of the cross sections at forward angles as reported in EXFOR and CSISRS. At 2 MeV, the discrepancy is a factor of two at  $\sim 30$  degrees. Because the ENDF database was derived from these datasets, it also shows the discrepancy. Spectra of the 1970s data are not available nor are descriptions of how the peak yields were stripped. In one case, i.e., the thesis data of Galati [Phys. Rev. C 5, 1508 (1972) and dissertation, University of Kentucky, 1969], we were able to obtain several spectra and information on how the yields were extracted from Galati's mentor, Jesse Weil, of the Institute of Isotopes in Budapest. For the Galati data sets between 3.0 and 6.9 MeV, peak yields were summed above a straight-line background, and this is likely the case for other neutron TOF spectra from that era. A re-analysis of the whole carbon differential cross section data is planned, pending the development of new neutron TOF fitting codes.

## $^3\text{H}(\text{p},\text{n})$ Cross Sections

The MAIN detector efficiency is required to correct scattered-neutron yields. Rather than attempting to model the detector efficiency with Monte Carlo or closed form expressions, we measure it directly for best accuracy. We make use of the  $^3\text{H}(\text{p},\text{n})$  angular distribution and  $^3\text{H}(\text{p},\text{n})$  kinematic angular variation. One must make a choice for the  $d\sigma/d\Omega_{\text{Tpn}}$  cross section. Recommended values may be taken from either: i) Liskien & Paulsen [Liskien & Paulsen, Nucl. Data Tables 11, 569, 1973], ii) DROSG-2000 [Drosg, IAEA-NDS-87 rev 8, Jan 2003] program series, or iii) the evaluated ENDF database [Hale, "p-T Reaction Evaluations" for NNDC, Dec 1999, Sept 2001, and Dec 2003]. ENDF angle-integrated cross sections are OK, but there is not enough detailed resonance parameter information for the R-matrix treatment to predict angular distributions. ENDF differential cross sections can differ as much as 15% from measured results and also generate non-physical behavior in the efficiency curves. The DROSG-2000 parameters are modernized LP descriptions.

## Multiple Scattering Corrections

The code MULCAT is used to perform attenuation and multiple scattering corrections on measured laboratory cross sections. In comparing to CSISRS data and ENDF model calculations, there is suspicion, although difficult to prove, that the code produces slightly higher differential cross sections at forward angles and slightly deeper minima. This suspicion is difficult to evaluate because that data originated in the late 1960s and early 1970s and the ability to evaluate data corrections was limited at that time. Optical model angular distributions buried in the ENDF database may also be suspect. Results of simulations with MCNPX reveal that the agreement with MULCAT is surprisingly good and that MULCAT is likely to perform much better than its own Monte Carlo-predicted calculational uncertainties (~10-13%). Differences at angles  $> 90^\circ$  are  $< 4\%$ . Significant differences occur in the region  $50-90^\circ$  and are as large as 30%, but are likely the result of imperfect MCNPX modeling approximations. We continue to investigate this issue. The differences could arise from our description of the beam uniformity and divergence. MULCAT uses a realistic Liskien & Paulsen angular neutron fluence profile and includes the actual gas cell dimensions, while the MCNPX simulation does not.

The sensitivity of differential cross section results to MULCAT input parameters for attenuation and multiple scattering corrections was also examined by University of Dallas student Leslie Sidwell. The following variations cause average changes in the differential cross sections by  $< 1\%$ : flight path ( $> 1''$ ), Na sample height (0.2 cm), and gas cell to sample distance (0.5 cm). One-percent effects can be seen with: decreased graininess of  $\sigma_{\text{tot}}$  values (20%) and Na sample radius (0.1 cm). All these input quantities are known much better than the specified 1% limits.

## Other Nuclear Data Activities

An overview of basic and applied research activities at the University of Kentucky Accelerator was presented at the Topical Meeting on Applications of Accelerators, AccApp13, with travel funds provided by the University of Kentucky. The meeting provided much information on how our  $^{23}\text{Na}$  and Fe cross sections will be incorporated into the fast-burner reactor designs. This meeting also offered a site visit to the Institute of Research on Materials and Measurements. The site visit provided an opportunity to interact with Arjan Plompen and Bjorn Becker at the GELINA accelerator facility and discuss activities for collaboration on cross-section measurements. The GELINA group was particularly interested in the discrepancies between their recent  $^{\text{nat}}\text{Li}(n,n'\gamma)$  measurements and those performed by Ron Nelson at GEANIE at Los Alamos National Lab. Both groups were curious whether measurements at the University of Kentucky could assist in resolving the discrepancy.

The NEMEA7/CIELO workshop in Nov 2013 was especially fruitful. CIELO is a 3-year working group with the goal of constructing better evaluations for  $^1\text{H}$ ,  $^{16}\text{O}$ ,  $^{56}\text{Fe}$ ,  $^{235,238}\text{U}$ , and  $^{239}\text{Pu}$ . The meeting's intent was to get people together from every part of nuclear data enterprise and stimulate communication. The workshop was very good for picking up the philosophy of how nuclear reaction codes, evaluations, reactor codes, physics data, engineering data, and covariance treatments fit together and interact. Much free time was available for discussion of the pros and

cons of existing nuclear data evaluations, reaction mechanism modeling, and experimental techniques. Meeting notes containing suggestions and requests for the UKAL team were provided in the quarterly report documents. All workshop presentations are available at <http://www.oecd-nea.org/science/wpec/nemea7/presentations.html>.

Sally Hicks presented a paper in the educational session of the CAARI-2014 (Conference on the Use of Accelerators in Research and Industry) in San Antonio on 25-30 May 2014. She discussed the contributions of undergraduate students in nuclear physics and nuclear data research.

University of Kentucky PI Steve Yates, UK Postdoc Erin Peters, and University of Dallas PI Sally Hicks traveled to the University of Notre Dame to contribute to the ARUNA (Association for Research at University Nuclear Accelerators) workshop on June 12 and 13, 2014. The purpose was to produce a white paper for input to the NSAC Long-Range Plan on behalf of the university laboratories. The white paper was presented at the Low-Energy Community Meeting, 21-23 August 2014, at Texas A&M University. ARUNA member Erin Peters presented the technical aspects of the facilities at UKAL; Steven Yates focused on the NEUP and NSF funded research that takes place at the laboratory; and Sally Hicks focused on the importance of such facilities for education.

The team sent representatives to the Workshop on Inelastic Neutron Scattering, WINS2014, at the Helmholtz Zentrum Dresden-Rossendorf Laboratory 3-5 December 2014 (<http://www.hzdr.de/db/Cms?pNid=3221>). A significant portion of the program dealt with measurements on  $^{56}\text{Fe}$ . Colleagues from the laboratories RPI, nELBE, LANSCE, and GELINA attended. Particularly fruitful discussions occurred on cross section normalizations, techniques for determining efficiencies of scintillator detectors, MCNP modeling of the experimental configurations, and the use of fission chambers at Van de Graaff accelerator labs.

Prof Sally Hicks contributed information on student involvement and workforce development to the document “Nuclear Science Education & Innovation” - a document prepared for the Nuclear Science Advisory Committee in support of the updated DoE and NSF Long Range Plan.

The CGS15 meeting was very productive. Meeting presentations are available at <http://www.hzdr.de/db/Cms?pNid=3140>. The team learned quite a bit about the impact of  $\gamma$ -ray generation on reactor applications. We also received valuable suggestions from scientists at HZDR-Rossendorf on how to eliminate noise with scintillator-phototube assemblies and thereby extend  $n/\gamma$  PSD selectivity to neutron energies below 300 keV. We learned that the spallation neutron sources do not have good sensitivity to weak reaction processes. This is because although those labs produce extremely high numbers of neutrons per pulse, there are extremely few neutrons of any given energy and the measurement techniques introduce cross talk into other energy regions. There were discussions on cross section standardization techniques at the spallation labs LANL, GELINA, & RPI versus TUNL versus UK. The spallation labs have a planar neutron beam and use a fission chamber to measure the absolute incident flux (with respect to  $U(n,f)$ ). TUNL also uses a fission chamber, but the low-mass actinide target is an integral part of the fission chamber. Neither of these two labs measures the energy of the outgoing neutrons nor the angular distributions, although there may be plans to construct an exit

channel neutron detector TOF system at GELINA. At UKAL, we standardize cross sections with respect to the extremely well known  $H(n,n)$  cross sections. After some thought, UK could implement a fission chamber to 'monitor' the absolute neutron flux, but in the end, this monitoring would be more ambiguous than the present relative measurement technique because of the divergent nature of our neutron source. The CGS15 meeting provided an excellent opportunity to recruit future postdocs because the students attending the meeting have experience working at neutron laboratories.

### Task/Objective/Deliverable/Milestone 3

Title: Personnel

#### Description

The project includes funding for 1-3 undergraduates and 1 postdoctoral fellow per year in addition to the principal investigators.

#### Accomplishments

##### Samuel Henderson

UD undergraduate physics major Samuel Henderson completed work on the elastic  $^{54}\text{Fe}(n,n)$  differential cross sections for his senior thesis project.

He attended the National Nuclear Chemistry Summer School - 2014 at SUNY-Stony Brook. This is an extremely selective program and only 12 slots are available at Stony Brook and there were in excess of 200 applicants. Feedback indicates Samuel placed among the top couple of students despite not being a 'true' chemist and not having a wet chemistry background. However, because of his physics background, he was in demand by fellow students during the physical chemistry sections of the course. The Nuclear Chemistry Summer School has been extremely successful in generating nuclear and radiochemistry graduate students.

Samuel finished thesis during the Fall 2014 semester for his B.S. degree. He received graduate school offers in nuclear physics at Michigan State University, NC State University, Notre Dame, and Texas A&M. He chose to pursue a nuclear physics Ph.D. at the University of Notre Dame beginning Fall 2015.

##### Leslie Sidwell

UD student Leslie Sidwell participated in much of the  $^{23}\text{Na}$  project. Her contribution was valuable for double-checking  $^{23}\text{Na}$  cross sections and mapping the sensitivity of the MULCAT multiple-scattering and attenuation corrections to perturbations in the input parameters. She became a high school mathematics and science teacher at Red Oak School District in Red Oak, Texas.

##### Shaohua Liu

UK postdoc Shaohua Liu completed analysis of nine  $^{54}\text{Fe}(n,n)$  data sets. He, with mentor Marcus McEllistrem, get the credit for discovering the reaction mechanism change between 4 and 5 MeV discussed above. Pending careful reconsideration of the enhanced direct strength in the  $(n,n_1)$  channel at  $E_n > 4$  MeV, we are preparing the final paper and will submit



results to the evaluators. Shaohua departed 31 Dec 2014 to take a job in radiation physics at the company West Physics in Atlanta, Georgia.

### Marcus McEllistrem

Professor Emeritus Marcus McEllistrem was inducted into the University of Kentucky Hall of Fame for his 50-years of contributions to the experimental nuclear physics program.

### Aaron French

UD chemistry major Aaron French analyzed the  $^{54}\text{Fe}(n,n'\gamma)$  and the  $^{nat}\text{V}(n,n'\gamma)$   $\gamma$ -ray production data that he helped take in January 2014 for his thesis project. He was selected to attend the National Nuclear Chemistry Summer School - 2014 at San Jose State University. This is an extremely selective program and only 12 slots are available at San Jose and there were in excess of 200 applicants. He was the top student at the summer school and won a free trip to the Spring 2015 American Chemical Society meeting 22-26 March in Denver. Like the SUNY-Stony Brook program, the Nuclear Chemistry Summer School has been extremely successful in generating nuclear and radiochemistry graduate students. Aaron gave an invited presentation at the Spring 2015 American Chemical Society meeting 22-26 March 2015 in Denver – this is a fantastic achievement for an undergraduate.

He had nuclear engineering graduate school offers from University of Michigan and Texas A&M. He chose to attend nuclear engineering graduate school at Texas A&M beginning Fall 2015.

### Trey Harrison

USNA undergraduate Trey Harrison learned to perform longitudinal-beam optics calculations on the pulsing system of the UKAL accelerator. He has discovered that the small tails appearing on the left and right sides of the large elastic scattering TOF peak are due to mismatching the time spread of the chopped pulse to the rf sine-wave which drives the buncher. If the chopped pulse is too wide it is impacted by the curvature of the sine wave driving the buncher, producing the small tails. One solution to this problem is using a smaller chopping aperture; however, this reduces the beam current. Another solution is to use a higher ion energy entering the pulsing system. The issue has a slight effect upon proton pulsed beams, but is extremely important for the higher energy neutron measurements with the  $\text{D}(d,n)$  reaction.

During May 2015 run he performed odds-and-ends calculations and explored using the GNUPLOT package to produce scientific quality figures and to fit Legendre polynomials to data. Microsoft Excel does not have advanced fitting routines.

He has accumulated extensive experience in cyber warfare.

Trey graduates in May 2016 and will be a USMC pilot.

### James Hansen

USNA undergraduate James Hansen began the Fall-2014 semester semester analyzing the  $^{56}\text{Fe}(n,p)$  data. He stripped all the data but dropped the project from his semester courses. The

data is stripped, but has not been converted to (n,p) cross sections. He will enter the nuclear propulsion program.

### Luke Pecha

UD undergraduate physics major Luke Pecha participated in both (n,n') measurements on the isotopically enriched  $^{54}\text{Fe}$  and  $^{56}\text{Fe}$  samples during Summer 2014. He has also been instrumental in assisting the other UD students in learning to analyze data. His personal senior thesis project is the  $^{54}\text{Fe}(n,n'\gamma)$  angular distribution at  $E_n = 4.50$  MeV. These data were taken to complement the excitation functions taken for  $E_n = 1.5 - 4.5$  MeV. His results will generate important information for cross sections by providing branching ratios, the spins and parities, and the Legendre polynomial coefficients to learn the size of the  $a_4$  coefficients needed for  $\gamma$ -ray production cross sections. Luke's data revealed the interesting pair of doublet  $\gamma$ -ray transitions at 3.106 MeV excitation in  $^{56}\text{Fe}$  discussed in a previous milestone.

He graduated in May 2015 and is taking a year to decide on advanced study in either nuclear physics or medical physics.

### Thaddeus Howard

UD undergraduate physics major Thaddeus Howard joined the project for both high-energy neutron measurements at UKAL on  $^{54}\text{Fe}$  and  $^{56}\text{Fe}$  during the summer. His senior thesis project is analysis of the  $^{\text{nat}}\text{Fe}(n,n'\gamma)$  data taken in January 2014 and he is investigating the use of  $^{\text{nat}}\text{Al}$  and  $^{\text{nat}}\text{Ti}$  as normalization references for the Fe  $\gamma$ -ray production cross sections. As it turns out, incredibly consistent cross section values were obtained. Thaddeus' data revealed the two transitions previously assigned to what is now considered an extraneous  $3^-$  level in  $^{56}\text{Fe}$  at low excitation; the existence of this level was debated during the Fe sessions at the BNL Nuclear Data week, 29 Oct-7 Nov 2014. The weakness of the  $\gamma$ -rays did not allow us to place the transitions, but we cannot eliminate the possibility that the level does exist.

He had graduate school offers from nuclear engineering at Texas A&M, mechanical engineering at Univ. Texas - Arlington, or medical physics at M.D. Anderson Cancer Center. Thaddeus will begin advanced study in medical physics at M.D. Anderson Cancer Center in Houston, Texas.

### Anthony Sigillito

Former UD student Anthony Sigillito worked on the  $^{23}\text{Na}$  project and is doing very well as a graduate student in Electrical Engineering at Princeton and is developing devices for quantum computing. He has become a prolific publisher.

### Shawn Nigam

UK undergraduate Shawn Nigam worked with the project for a semester and in July 2014. He learned to program in FORTRAN and wrote several codes to graphically compare our results to information from EXFOR & CSISRS, and the databases ENDF, JENDL, and JEFF. He has changed his major to Mathematical Economics.

### Brandon Thompson

USNA undergraduate Brandon Thompson analyzed the  $^{54}\text{Fe}(n,n')$  and  $^{56}\text{Fe}(n,n')$  angular distribution data at 6.0 MeV to make a secondary check on postdoc Shaohua Liu's results. Brandon participated in the Nov 2014 measurements, funded by ONR Midshipman Research. He graduated in 2015 and is a pilot for the USMC.

### Ben Rice

USNA undergraduate Benjamin Rice worked with the project for 2.5 years. His expertise is MCNP calculations.

He performed the initial MCNP calculations from which we gained advanced knowledge of the energetics of multiple scattering and its effect upon the neutron tof spectra. This led to recognition of the  $^{12}\text{C}$  problem discussed previously.

He reduced the 5.0 MeV  $^{54}\text{Fe}(n,n')$  and  $^{56}\text{Fe}(n,n')$  angular distributions in order to make a secondary check on postdoc Shaohua Liu's results.

Ben performed MCNP calculations to understand how neutrons propagate through the tantalum wedge used to shield our main neutron detector from the gas cell.

He performed MCNP calculations to study the impact of tritium gas cell construction on efficiency measurements. Neutrons emerging from the gas cell must pass through the stainless steel walls of the gas cell and its Ta liner. There are also effects from source neutrons scattering from the adjacent beamline components. The investigation indicates one should not measure MAIN detector efficiencies at angles  $>140^\circ$  because scattering from the beamline construction has a major impact. Fortunately, the kinematics of our reactions and the lower discriminator threshold on the MAIN neutron detector do not require us to make measurements at angles  $>140^\circ$ .

During the May-2015 experimental run, he taught UD students Thienan and Daniel how to use MCNP.

Ben also started a project to develop a collimated neutron beam facility in the second experimental hall at the accelerator lab. The idea is to create a well-defined planar beam of neutrons which would enable scattering studies with unshielded detectors. This facility could enable the use of unshielded detectors for other DOE and DHS applications.

He has started graduate school at Johns Hopkins University - Applied Physics Lab although he does not technically graduate from USNA until May 2016.

### Anthony Ramirez

Postdoc Anthony Ramirez joined the team in March 2015. He did his graduate work at Ohio University Accelerator Laboratory and this has provided a wonderful boost to our program as he already understands many of the concepts of neutron scattering. His insight into neutron scattering at the higher incident energies is valuable. He rapidly came up to speed and has completed analysis of twelve  $^{56}\text{Fe}(n,n)$  angular distributions and of three  $^{56}\text{Fe}(n,n')$  angular distributions. Anthony gave an oral presentation at the October 2015 APS Division of Nuclear

Physics meeting in Santa Fe. He is running the on-site nuclear data program at the accelerator lab.

#### ThienAn Nguyen

UD physics major ThienAn Nguyen joined the team in the May 2015. ThienAn has learned the basics of MCNP and VisEd and with colleague Daniel Jackson, has constructed a complete model of the University of Kentucky Accelerator laboratory including walls, floor, ceiling, and interior shielding walls. ThienAn is investigating the neutron spectrum at various locations in the laboratory for the  $d+^2\text{H}$  neutron production reaction at  $E_n = 7$  MeV and how those spectra are influenced by walls, flooring geometry, and the position of the main detector carriage. ThienAn received an APS:DNP:CEU award to attend the October 2015 APS Division of Nuclear Physics meeting in Santa Fe. To date, he has received offers from the nuclear engineering program at the University of Florida and the medical physics program at the University of Kentucky. ThienAn will graduate in May 2016 and will likely start a Medical Physics program in Aug 2016 at either University of Kentucky or Oregon State.

#### Daniel Jackson

UD physics major Daniel Jackson participated in the May-June-July 2015 runs. Daniel learned the basics of MCNP and VisEd and with colleague ThienAn Nguyen, has constructed a complete model of the University of Kentucky Accelerator laboratory including walls, floor, ceiling, and interior shielding walls. Daniel is investigating the neutron spectrum at various locations in the laboratory for the  $p+^3\text{H}$  neutron production reaction at  $E_n = 4$  MeV and how those spectra are influenced by walls, flooring geometry, and the position of the main detector carriage. Daniel received an APS:DNP:CEU award to attend the October 2015 APS Division of Nuclear Physics meeting in Santa Fe. During the poster session, Daniel was caught giving MCNP advice to other undergraduate and graduate students. Daniel will graduate in May 2016 and plans to start graduate school in either nuclear physics or nuclear astrophysics in August 2016 at Louisiana State, Baylor, or Texas Christian.

#### Philip Lenzen

UD rising-sophomore physics major Philip Lenzen began work with the group during the June-July 2015 runs. Colleagues Thienan and Daniel taught him the basics of MCNP. Philip is investigating the neutron spectrum at various locations in the laboratory for the  $d+^3\text{H}$  neutron production reaction at  $E_n = 17$  MeV. The laboratory has performed a few high neutron energy measurements and we need to investigate complications and the radiation fields introduced at these high neutron energies.

#### Daniel Alcorn-Dominguez

USNA undergraduate Daniel Alcorn-Dominguez is performing calculations with the optical model code CINDY – typically used to analyze  $(n,n'\gamma)$  data. CINDY produces  $a_2$  &  $a_4$  Legendre coefficients, substate alignments, and transmission coefficients. The UKAL makes  $\gamma$ -ray excitation function measurements at  $125^\circ$ . To convert these to angle-integrated cross

sections, we assume that the  $a_4P_4$  term in the angular correlation is negligible. Daniel will be studying how the  $a_2$  &  $a_4$  coefficients and substate alignments vary as a function of incident neutron energy. The work is important for understanding how the Optical Model is able to produce neutron cross sections and how sensitive the  $\gamma$ -ray angular distributions are to the incident neutron energy. We discovered several major features of the  $^{56}\text{Fe}$  (n,n') cross sections. Individual transmission coefficients calculated with CINDY/SCAT show the wavelength matching oscillations similar to those that are discussed in introductory quantum mechanics classes on rectangular barrier penetration. If this holds up to further scrutiny, a substantial portion of the jitter observed in the  $^{56}\text{Fe}$  cross sections may be due to wavelength – barrier thickness matching in the Optical Model description. These calculations must be tested against the TALYS/ECIS06 code. Finally, he observes that the substate population can only be treated as Gaussian for energies less than  $\sim 1$  MeV above the level threshold.

#### George Kehlert

USNA sophomore undergraduate George Kehlert is learning about accelerator operation at the USNA accelerator in hopes of working with the project beginning in Summer 2016.

#### The University of Kentucky postdocs: Erin Peters, Ben Crider, Francisco Prados-Estévez, Tim Ross, and Sharmistha Mukhopadhyay

Although not funded by the NEUP project, other personnel at the UKAL contribute to the project. UK graduate student Erin Peters has remained at UK as a postdoc and lecturer and is extremely helpful in running the research group and mentoring students. Postdoc Tim Ross who assisted with the accelerator operation and was responsible for many shifts during out experiments has returned to Scotland where he is examining his career options. Sharmistha Mukhopadhyay brings her detector experience from a post-graduate school position at RMD.

#### **Other Relevant Information:**

Name	Country	Area of Study	Year of Completion	Status	Current Location
Jordan Potter	--	Pharmacy/Chemistry	2015	Undergrad	Univ Kentucky Pharmacy School
Ben Crider	--	Physics	2014	Grad; Ph.D.	Postdoc, MSCL/FRIB, Michigan State
Erin Peters	--	Chemistry	2014	Grad; Ph.D.	Postdoc/Instructor Univ Kentucky
Francisco Prados-Estévez	Spain	Physics	2014	Postdoc	Target Technology Inc Irvine CA

Brian Champine	--	Nucl Eng	2016	Grad; Ph.D.	In grad school, Nuclear Phys, UCal Berkley
Brett Combs	--	Physics	2013	Undergrad	Compass Minerals, Accounts Analyst
Tim Ross	U.K.	Physics	2014	Postdoc	
Leslie Sidwell	--	Physics	2013	Postgraduate	High School Physics Teacher Red Oak TX
Samuel Henderson	--	Physics	2015	Undergrad	In grad school, Nucl Physics, Notre Dame
Evaristo Garza	--	Physics	2015	Undergrad	USNavy
Joshua Steves	--	Math & Physics	2015	Undergrad	In grad school, Mathematics, Oxford Univ
Shaohua Liu	China	Physics	2014	Postdoc	Radiation Physicist, West Physics, Atlanta, GA
Aaron French	--	Chemistry	2015	Undergrad	In grad school, Nucl Eng, Texas A&M
Trey Harrison	--	Physics	2016	Undergrad	Future: USMC Pilot
James Hansen	--	Physics	2016	Undergrad	Future: USN Nucl Propulsion
Zach Santonila	--	Physics	2014	Undergrad	In grad school, Electrical Eng, Notre Dame
Benjamin Rice	--	Physics	2016	Undergrad	In Grad School, Applied Physics, Johns Hopkins Univ
Luke Pecha	--	Physics	2015	Undergrad	Currently deciding on grad school in either Nucl Phys or Med Phys
Thaddeus Howard	--	Physics	2015	Undergrad	In grad school, Medical Physics, MD Anderson, Houston TX
Shawn Nigam	--	Chemistry	2016	Undergrad	
Erin Peters	--	Chemistry		Postdoc	Postdoc/Instructor Univ Kentucky
Brandon Thompson	--	Physics	2015	Undergrad	US Marine Corps
Anthony Ramirez	Philippines	Physics	2017	Postdoc	Postdoc, Univ Kentucky
Thienan Nguyen	--	Physics	2016	Undergrad	Accepted into Med Physics, @ 2 Universities
Daniel Jackson	--	Physics	2016	Undergrad	Planning grad school Astrophysics following graduation
Philip Lenzen	--	Physics	2018	Undergrad	Presently a Junior
Sharmistha Mukhopadhyay	India	Physics		Postdoc	Postdoc, Nuclear Physics, Univ Kentucky
Anthony Alcorn-Dominguez	--	Physics	2016	Undergrad	US Navy, NFO
George Kehlert	--	Physics	2018	Undergrad	Presently a Junior

#### **Task/Objective/Deliverable/Milestone 4**

Title: Procurement

##### Description

Procure isotopically enriched  $^{54}\text{Fe}$  and  $^{56}\text{Fe}$  to be used as scattering samples during the 2<sup>nd</sup> and 3<sup>rd</sup> years. Procure related auxiliary equipment and repair items.

##### Accomplishments

The HPGe  $\gamma$ -ray detector was annealed to repair neutron damage incurred during the (n,n' $\gamma$ ) measurements. The Kmax<sup>TM</sup> data acquisition software was updated.

All equipment items have been received from the vendors: a time-to-amplitude converter, vacuum gauges, and a second forward-monitor neutron detector have been purchased. All of these are <\$5000 items.

An enriched  $^{54}\text{Fe}$  sample was the focus of measurements during Year-2. Measurements were completed and the sample returned to Oak Ridge Isotope Sales in June 2014.

The leased enriched  $^{56}\text{Fe}$  sample was received from Oak Ridge Isotope Sales in late June 2014. Because of the extensive use of the  $^{56}\text{Fe}$  sample in cross sections normalization, the sample was purchased.  $^{56}\text{Fe}$  measurements were the focus of measurements during Year-3.

**Materials & Supplies Procurement Information**  
(only required for items >\$5000)

	Description	Pr op #	Manufacturer	Serial Number	Acquisition Date	Unit Price	Qty	Total Cost	Location
1	MPD-4 Pulse Shape Discriminator Module	--	MESYTEC	0811173	Nov 2012	\$5985	1	\$5985	Chem-Physics Bldg, Room 63
2	Ortec 576 Time-to-Amplitude Converter	--	EG&G Ortec	12341937	Nov 2012	\$2552	1	\$2552	Chem-Physics Bldg, Room 63
3	Ortec 556H High Voltage Power Supply	--	EG&G Ortec	03036092 03036093	Nov 2012	\$2626	2	\$5252	Chem-Physics Bldg, Room 63
4	C6D6 n-Detector, 25mm 107 A 25.4 / 3M-E1-EJ315	--	Scionix	SFF402	April 2013	\$3990	1	\$3990	Chem-Physics Bldg, Room 63
5	C6D6 n-Detector, 51mm 107 A 51 / 3M-E1-EJ315	--	Scionix	SFF401	April 2013	\$5960	1	\$5260	Chem-Physics Bldg, Room 63
6	<sup>56</sup> Fe Sample purchase	--	ORNL-Isotope Office	n/a	June 2014	~\$23000	1	~\$23000	Chem-Physics Bldg, Room 63 & 127
7	<sup>54</sup> Fe Sample lease	--	ORNL-Isotope Office	n/a	May 2013 to June 2014	\$ 12133	1	\$ 12133	returned to ORNL Isotope Office
8	Ortec 576 Time-to-Amplitude Converter	--	EG&G Ortec	14062250	May 2014	\$2552	1	\$2552	Chem-Physics Bldg, Room 63
9	Vacuum Gauge	--	Granville-Philips	358B3222	May 2014	\$2662	1	\$2662	Chem-Physics Bldg, Room 63
10	EJ301 Scintillator, 107 mm x 25mm	--	Scionix	SBN-189	June 2014	\$3895	1	\$3895	Chem-Physics Bldg, Room 63
11	<sup>56</sup> Fe Sample purchase	--	ORNL-Isotope Office	n/a	Nov 2014	\$10544	1	\$10544	Chem-Physics Bldg, Room 63
12	Turbopump	--	Osaka Vacuum	TG60	Nov 2015	\$3315	2	\$6630	Chem-Physics Bldg, Room 63



## Presentations and Publications

(items marked “\*” are by association)

FY13

Invited Presentation: “Basic and Applied Science Using Monoenergetic Pulsed Neutron Beams from the University of Kentucky Accelerator Laboratory”, J.R. Vanhoy, S.F.Hicks, H.E.Baber, B.P.Crider, E.E.Peters, F.M. Prados-Estévez, T.J.Ross, M.T.McEllistrem, S.W.Yates, 11<sup>th</sup> International Topical Meeting on Nuclear Applications of Accelerators: AccApp’13, Bruges, Belgium, 5-8 Aug 2013.

Conf Publication: “Basic and Applied Science Using Monoenergetic Pulsed Neutron Beams from the University of Kentucky Accelerator Laboratory”, J.R. Vanhoy, S.F.Hicks, H.E.Baber, B.P.Crider, E.E.Peters, F.M. Prados-Estévez, T.J.Ross, M.T.McEllistrem, S.W.Yates, 11<sup>th</sup> International Topical Meeting on Nuclear Applications of Accelerators: AccApp’13, Bruges, Belgium, 5-8 Aug 2013.

Publication: “Measurements with Monoenergetic Fast Neutrons at the University of Kentucky Accelerator Laboratory”, in *Compendium of Accelerator Facilities for Nuclear Data Measurements, Use of Neutron Beams for High Precision Data Measurements*, editors Danas Ridkias and Tamas Belgia, Feb 2013,  
[http://www.iaea.org/OurWork/ST/NE/NEFW/Technical\\_Areas/RRS/documents/TM\\_Neutron\\_Beams\\_for\\_ND.pdf](http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/documents/TM_Neutron_Beams_for_ND.pdf)

Conf Publication: “Elastic and Inelastic Neutron Scattering Cross Sections for Fission Reactor Applications”, S. F. Hicks, A. Chakraborty, B. Combs, B. P. Crider, L. Downes, J. Girgis, L. J. Kersting, A. Kumar, C. J. Lueck, P. J. McDonough, M. T. McEllistrem, E. E. Peters, F. M. Prados-Estévez, J. Schniederjan, L. Sidwell, A. J. Sigillito, J. R. Vanhoy, and S. W. Yates, In Proceedings of the 22<sup>nd</sup> International Conference on Applications of Accelerators in Research and Industry 2012, AIP Conf. Proceedings 1525, ed F.D. McDaniel and B.L. Doyle, Melville: AIP p.276 (pub 19 Apr 2013). <http://dx.doi.org/10.1063/1.4802333>

Publication: “Comparison of deuterated and normal scintillators for fast-neutron detection”, V. Bildstein, P.E. Garrett, J. Wong, D. Bandyopadhyay, J. Bangay, L. Bianco, B. Hadinia, K.G. Leach, C. Sumithrarachchi, S.F. Ashley, B.P. Crider, M.T. McEllistrem, E.E. Peters, F.M. Prados-Estévez, S.W. Yates, J.R. Vanhoy, Nucl. Instrum. Meth. A 729, 188 (2013). <http://dx.doi.org/10.1016/j.nima.2013.06.082>

Poster Presentation: “Differential Cross Sections for Neutron Elastic and Inelastic Scattering on <sup>23</sup>Na” 03091 J.R. Vanhoy, S.F. Hicks, A. Chakraborty, B.R. Champine, B. Combs, B.P. Crider, L.J. Kersting, A. Kumar, C.J. Lueck, P.J. McDonough, M.T. McEllistrem, E.E. Peters, F.M. Prados-Estévez, L. Sidwell, A. Sigillito, D.W. Watts and S.W. Yates, International Nuclear Physics Conference INPC2013: 2-7 June 2013, Firenze, Italy

\*Poster Presentation: “Inelastic Neutron Scattering on <sup>160</sup>Gd”, S. R. Leshner, C. Casarella, B. P. Crider, R. Ikeyama, I. Marsh, E. E. Peters, F. M. Prados-Estévez, M. K. Smith, Z. Tully, J. R. Vanhoy, A. Aprahamian and S. W. Yates International Nuclear Physics Conference INPC2013: 2-7 June 2013, Firenze, Italy

\*Poster Presentation: “Level Lifetimes in <sup>94</sup>Zr from DSAM Measurements following Inelastic Neutron Scattering 02111 S. W. Yates, E. E. Peters, A. Chakraborty, B. P. Crider, M. T. McEllistrem, F. M. Prados-Estévez and J. R. Vanhoy International Nuclear Physics Conference INPC2013: 2-7 June 2013, Firenze, Italy

\*Poster Presentation: “Nuclear structure study of <sup>106</sup>Pd and <sup>106</sup>Cd with the (n,n’ $\gamma$ ) reaction” 02085, F.M. Prados-Estévez, A. Chakraborty, E.E.Peters, M.G.Mynk, A.Linnemann, D.Bandyopadhyay, N.Boukharouba, S.N.Choudry, B.P.Crider, P.E.Garrett, S.F.Hicks, J.Jolie, A.Kumar, S.R.Leshner, C.J.McKay, M.T.McEllistrem, S.Mukhopadhyay, J.N.Orce, M.Scheck, J.R.Vanhoy, J.L.Wood, and S.W.Yates, International Nuclear Physics Conference INPC2013: 2-7 June 2013, Firenze, Italy

\*Publication: “Level lifetimes in the stable Zr nuclei: Resolution of the  $^{94}\text{Zr}$  anomaly” E.E. Peters, A. Chakraborty, B.P. Crider, B.H. Davis, M.K. Gnanamani, M.T. McEllistrem, F.M. Prados-Estévez, J.R. Vanhoy, and S.W. Yates, Phys. Rev. C 88, 024317 (2013). DOI: <http://dx.doi.org/10.1103/PhysRevC.88.024317>

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Presentation: “The Neutron Time-of-Flight Cross Section Program at the University of Kentucky – Adventures in Analysis II”, J.R. Vanhoy, S.F. Hicks, B.P. Crider, A.J. French, E.A. Garza, S.L. Henderson, T.J. Howard, S.H. Liu, S. Nigam, L. Pecha, E.E. Peters, F.M. Prados-Estévez, M.T. McEllistrem, B.G. Rice, T.J. Ross, Z.C. Santonil, L.C. Sidwell, J.L. Steves, and S.W. Yates. The XVth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Dresden, Germany, 25-29Aug 2014

\*Presentation: “Inelastic Neutron Scattering Studies of  $^{76}\text{Ge}$  and  $^{76}\text{Se}$ : Relevance to Neutrinoless Double- $\beta$  Decay”, B.P. Crider, J.M. Allmond, M.T. McEllistrem, E.E. Peters, F.M. Prados-Estévez, T.J. Ross, J.R. Vanhoy, and S.W. Yates, The XVth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Dresden, Germany, 25-29Aug 2014

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FY15

Presentation: “Inelastic Neutron Scattering Cross Sections from Gamma-Ray Production Cross Sections in  $^{54}\text{Fe}$  and  $^{56}\text{Fe}$ ,” S. F. Hicks, J. R. Vanhoy, B.P. Crider, A.J. French, T.J. Howard, S.H. Liu, M.T. McEllistrem, R. L. Pecha, E.E. Peters, F.M. Prados-Estévez, T.J. Ross, Z.C. Santonil, and S.W. Yates, WINS2014 Helmholtz-Zentrum Dresden-Rossendorf, Germany, Dec. 3-5, 2014.

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Presentation: “Determination of Decay Characteristics of  $^{54}\text{Fe}$  Excited Levels through Inelastic Neutron Scattering,” Robert L. Pecha, S.F. Hicks, A.J. French, S.L. Henderson, Z.C. Santonil, L.C. Sidwell, M.T. McEllistrem, E.E. Peters, T.J. Ross, and S.W. Yates, J.R. Vanhoy and B.K. Thompson, presented at the TX APS Fall Meeting at TX A&M University, Oct. 17-19, 2014.

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Presentation: “The neutron detector array DESCANT”, V. Bildstein, P.E. Garrett, D. Bandyopadhyay, J. Bangay, L. Bianco, G. Demand, B. Hadinia, K.G. Leach, C. Sumithrarachchi, J. Wong, S.F. Ashley, B.P. Crider, M.T. McEllistrem, E.E. Peters, F.M. Prados-Estévez, S.W. Yates, J.R. Vanhoy, G.C. Ball, A.B. Garnsworthy, G. Hackman, C.J. Pearson, F. Sarazin. Annual Meeting of the Division of Nuclear Physics, American Physical Society, Waikoloa, Hawaii, 7-11 Oct 2014.

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Invited Presentation: “Investigating the Neutron Inelastic Scattering Cross Sections for  $^{54}\text{Fe}$  through  $\gamma$ -Ray Spectroscopy”, Aaron J. French, S. F. Hicks, B. P. Crider, T. J. Howard, S.H.Liu, M. T. McEllistrem, R. L. Pecha, Erin E. Peters, F. M. Prados-Estévez, T. J. Ross, Z. C. Santonil, J. R. Vanhoy, Steven W. Yates American Chemical Society Meeting, Denver CO, 22-26 March 2015

Senior Thesis: “Determination of Level Structure for  $^{54}\text{Fe}$  Through Inelastic Neutron Scattering”, R.L. Pecha, Senior Thesis: University of Dallas, 2015

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Publication: “The Neutron Time-of-Flight Cross Section Program at the University of Kentucky – Adventures in Analysis II”, J.R. Vanhoy, S.F. Hicks, B.P. Crider, A.J. French, E.A. Garza, S.L. Henderson, T.J. Howard, S.H. Liu, S.Nigam, L. Pecha, E.E. Peters, F.M. Prados-Estévez, M.T. McEllistrem, B.G. Rice, T.J. Ross, Z.C. Santonil, L.C. Sidwell, J.L. Steves, and S.W. Yates. The XVth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Dresden, Germany, 25-29Aug 2014. EJP Web of Conferences, vol 93, ed Schwenger and Zuber, ISBN: 978-2-7598-1794-8, (May 2015), <http://dx.doi.org/10.1051/epjconf/20159302014>

Publication: “Undergraduate Measurements of Neutron Cross Sections”, S. F. Hicks, J. R. Vanhoy, A. J. French, Z. C. Santonil, B. P. Crider, E. E. Peters, M. T. McEllistrem, F. M. Prados-Estévez, T. J. Ross, and S.W. Yates. 23<sup>rd</sup> International Conference on Applications of Accelerators in Research and Industry 2014, San Antonio TX, 25-30 May 2014. Physics Procedia 66, 641 (2015). <http://dx.doi.org/10.1016/j.phpro.2015.05.085>

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\*Publication: “No-spin” states and low-lying structures in  $^{130}\text{Xe}$  and  $^{136}\text{Xe}$ , T.J. Ross, E.E. Peters, A. Chakraborty, B.P. Crider, A. Kumar, S.H. Liu, M.T. McEllistrem, F.M. Prados-Estévez, J.R. Vanhoy and S.W. Yates, The XVth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Dresden, Germany, 25-29 Aug 2014. EJP Web of Conferences, vol 93, ed Schwenger and Zuber, ISBN: 978-2-7598-1794-8, (May 2015), <http://dx.doi.org/10.1051/epjconf/20159301010>

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University of Kentucky contribution to the whitepaper “Nuclear Data Needs and Capabilities for Applications”, senior editors L. Bernstein and D. Brown, planning meeting at Lawrence Berkley National Lab, Berkley, CA 27-29 May 2015. Available online at <http://bang.berkeley.edu/events/ndnca/>

#### FY16

Presentation: “Elastic and inelastic scattering of neutrons from  $^{56}\text{Fe}$ ”, A.P. Ramirez, M. T. McEllistrem, S.H. Liu, S. Mukhopadhyay, E.E. Peters, S.W. Yates, J. R. Vanhoy, T.D. Harrison, B.G. Rice, B.K. Thompson, S. F. Hicks, T. J. Howard, D.T. Jackson, P.D. Lenzen, T.D. Nguyen, R.L. Pecha, Annual Meeting of the Division of Nuclear Physics, American Physical Society, Santa Fe, NM, 27-31 Oct 2015.

Poster Presentation: “Neutron Scattering Simulations at the University of Kentucky Accelerator Laboratory”, Thien An Nguyen, Daniel Jackson, S.F. Hicks, B. Rice, J.R. Vanhoy, Annual Meeting of the Division of Nuclear Physics, American Physical Society, Santa Fe, NM, 27-31 Oct 2015.

Poster Presentation: “MCNP Neutron Simulations: The Effectiveness of the University of Kentucky Accelerator Laboratory Pit”, Daniel Jackson, Thien An Nguyen, S.F. Hicks, B. Rice, J.R. Vanhoy, Annual Meeting of the Division of Nuclear Physics, American Physical Society, Santa Fe, NM, 27-31 Oct 2015.

Poster Presentation: “Neutron Scattering Studies at the University of Dallas: MCNP Modeling and Experimentation”, S. F. Hicks, A. French, Daniel Jackson, Thien An Nguyen, Luke Pecha, Thaddeus Howard, Ben Rice, J.R. Vanhoy, E.E. Peters, M. T. McEllistrem, A. P. Ramirez, and S.W. Yates, DOE-NNSA Stewardship Science Academic Program, Bethesda, MD, 17-18 Feb 2016.

Poster Presentation: “Differential Neutron Elastic and Inelastic Scattering Cross Section Measurements on Structural-Related Materials at the University of Kentucky Accelerator Lab”, J.R. Vanhoy, S.F. Hicks, M.T. McEllistrem, S. Mukhopadhyay, E.E. Peters, A.P. Ramirez, and S.W. Yates, DOE-NNSA Stewardship Science Academic Program, Bethesda, MD, 14-18 Feb 2016

## **Attachments**

1. FY16-Final 12-3411 Prog Report (this document)

## **Distribution**

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